Forecasting Gulf's Hypoxia: The Next 50 Years?

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ABSTRACT

Two critical questions surfaced during development of the Action Plan to reduce, mitigate, and control Gulf hypoxia. The first question was: “When did large-scale hypoxia start in the Gulf of Mexico?” The second question was: “What nitrogen load reduction would be needed to reach the societal goal set for hypoxia?” The Action Plan included a goal to reduce the five-year running average size of the hypoxic zone to below 5,000 km^2 by 2015. Knowing the answers to these questions is important both for understanding the underlying causes for Gulf hypoxia and for identifying reasonable and practical goals for reducing its size. The existing hypoxia models for the northern Gulf of Mexico range from simple regression models to complex 3-D simulation models, and they capture very different aspects of the physics, chemistry and biology of this region. Several of these models were successfully calibrated to observations relevant for their process formulations and spatial-temporal scales. Available model results are compared to reach the consensus that large-scale hypoxia probably did not begin in the Gulf of Mexico until the mid-1970s, and that the 30% nitrogen load reduction that is called for by the Action Plan may not be sufficient to achieve its goal. The present model results suggest that a 40-45% reduction in riverine nitrogen load may be necessary to achieve the desired reduction in the areal extent of hypoxia. These model results underscore the importance of setting this goal as a running average because of significant inter-annual variability. Caution is raised for setting resource management goals without considering the long-term consequences of climate variability and change.

This paper discusses the use of hypoxia models in synthesizing the knowledge about the causes of hypoxia, predicting the probable consequences of management actions, and building a

consensus about the management of hypoxia. It also offers suggestions for future efforts related to simulating and forecasting Gulf hypoxia.

INTRODUCTION

Large-scale hypoxia (< 2 mg O_2 l^{-1}) in the northern Gulf of Mexico (Figs. 1 and 2), up to 22,000 km^2, overlaps with habitat and fishing grounds of commercially important fish and shrimp. Hypoxia typically occurs from March through October in waters below the pycnocline, and extends between 5 and 60 m depth offshore (Rabalais and Turner 2001). Retrospective analyses (Eadie et al. 1994; Turner and Rabalais 1994; Sen Gupta et al. 1996) and model simulations (Justić et al. 2002; Scavia et al. 2003, 2004) suggest that Gulf hypoxia has intensified during the last five decades, as a probable consequence of increased riverine nitrogen inputs and more balanced nutrient ratios in discharged fresh waters (Turner and Rabalais 1991; Justić et al. 1995a, b; Goolsby et al. 1999; Turner et al. 2006). The concentration of nitrate, the predominant form of nitrogen in the Mississippi River, has increased 2.5-fold since the 1950s (Fig. 3), coincidentally with the increased use of fertilizer in the watershed (Turner and Rabalais 1991; Howarth et al. 1996; Goolsby et al. 1999). Nitrogen is often considered to be the limiting nutrient for estuarine and coastal phytoplankton (e.g., D'Elia et al. 1986; LimnoTech, Inc. 1995; Rabalais 2004), and there is strong evidence that it controls the extent of primary production in the northern Gulf of Mexico (Lohrenz et al. 1990, 1997, 1999; Rabalais et al. 2002).

Hypoxia develops from a suite of biological and physical factors, two of which are most important: (1) nutrient-enhanced surface primary productivity, which is also manifested in a high carbon flux to sediments (Justić et al. 1996; Lohrenz et al. 1997; Rabalais and Turner 2001) and (2) high stability of the water column, which controls vertical diffusive oxygen flux (Wiseman et al. 1997, 2004). Changes in the areal extent of hypoxia between flood years and drought years provide perhaps the best example of the synergistic nature of these influences. During the drought of 1988 (a 52-year low discharge record of the Mississippi River), bottom oxygen concentrations were significantly higher than normal, and formation of a continuous hypoxic zone along the coast did not occur that summer. The opposite was the case during the flood of 1993 (a 62-year maximum discharge for June-September), when the areal extent of summertime hypoxia showed a two-fold increase with respect to the average hydrologic year (Rabalais et al. 1998). The 1993 event was associated with both increased stability of the water column and nutrient-enhanced primary productivity, as indicated by the greatly increased nutrient concentrations and phytoplankton biomass in the coastal waters (Rabalais et al. 1998).

Because of potential ecological and economic impacts, as well as the implications for nutrient management in the Mississippi River watershed, Gulf hypoxia has received considerable scientific and public attention. In 2001, the Mississippi River Nutrient/Gulf of Mexico Hypoxia Task Force set a goal to reduce the 5-year running average of the Gulf's hypoxic zone to less than 5,000 km^2 by the year 2015 (Task Force 2001; Rabalais et al. 2002). The action plan suggested that a 30% decrease in nitrogen load was needed to reach this goal, and that the plan's implementation should be based on voluntary, incentive-based strategies applied to the watershed.

While the linkage between the anthropogenic nutrient inputs and hypoxia was addressed in the Action Plan (Task Force 2001), the importance of climatic factors has not received full consideration. There are several lines of evidence, however, suggesting that climatic factors profoundly influence the decadal and inter-annual variability of hypoxia in the northern Gulf of Mexico. First, the average Mississippi River discharge increased 30% since the 1950s, which contributed to the overall increase in nitrate flux (Goolsby et al. 1999; Justić et al. 2003b). Second, development of hypoxia in the northern Gulf of Mexico is highly sensitive to inter-annual variability in the Mississippi River discharge, as evidenced by changes in the areal extent and severity of hypoxia between flood and drought years (Fig. 2; Rabalais et al. 1998). Although the size of the hypoxic zone has varied greatly over the past 21 years, it has been significantly larger in wet years, compared to dry years (Rabalais et al. 1996; Rabalais et al. 1999; Rabalais and Turner 2001). Both the drought of 1988 and the flood of 1993 were caused by anomalous precipitation patterns associated in part with the El Nino/Southern Oscillation (ENSO) cycle (Trenberth and Guillemot 1996). During 1988, a particularly strong cool ENSO phase (La Nina) in the tropical Pacific triggered a series of anomalous circulation events that are believed to be responsible for the drought. In contrast, the 1993 flood was partly the outcome of an extended warm ENSO phase (El Nino).

BUILDING A CONSENSUS

Two critical questions surfaced during development of the Action Plan to reduce, mitigate, and control Gulf hypoxia (Task Force 2001; Rabalais et al. 2002). The first question was: “When did large-scale hypoxia start in the Gulf of Mexico?” The second question was: “What nitrogen load reduction would be needed to reach the societal goal set for hypoxia?” The Action Plan included a goal to reduce the five-year running average size of the hypoxic zone to below 5,000 km^2 by 2015. Knowing the answers to these questions is important both for understanding the underlying causes for Gulf hypoxia and for identifying reasonable and practical goals for reducing its size. If large-scale hypoxia, for example, was common before the significant increase in riverine nitrogen loads, it would not be reasonable to consider those loads as a primary cause. Also, if hypoxia is strongly affected by the variability in climatic factors, then different nutrient control end-points may be required to reach the same goal for hypoxia.

A number of different simulation and statistical models were used to nowcast, hindcast and forecast the severity and areal extent of hypoxia in the northern Gulf of Mexico (Table 1). Bierman et al. (1994), for example, developed a variation of the U.S. EPA Water Analysis Simulation Program (WASP) and applied it to a 21-segment, three-dimensional spatial grid on the Louisiana inner shelf. Chen et al. (1997) applied a coupled physical-biological model to study the influence of river discharge on the Louisiana-Texas shelf. Justić et al. (1996, 2002, 2003a) developed a time-dependent, coupled physical-biological, 2-box model, in order to study the oxygen cycling in the core region of the Gulf's hypoxic zone. Scavia et al. (2003, 2004) developed a variation of river dissolved oxygen model (= Streeter-Phelps model) that predicts hypoxic zone length using advection velocities for the bottom layer. Additionally, a number of simple and multiple regression models were developed that predict the areal extent of hypoxia based on riverine freshwater and nutrient fluxes (e.g., Goolsby et al. 2003; Turner et al. 2005, 2006).

Hindcasts of the areal extent of hypoxia in the Gulf of Mexico (Fig. 4) suggest that large hypoxic regions were not likely to have been present prior to the mid-1970s and that the size of those regions grew steadily until the mid 1980s (Scavia et al. 2003). Hindcasts of sub-pycnoclinal oxygen concentrations (Justić et al. 2002) suggest that summertime oxygen minima in the central section of the Gulf's hypoxic zone between 1955 and 1969 were fairly constant, always > 2 mg l^{-1} and most often > 4 mg l^{-1} (Fig. 4). The oxygen concentrations decreased during the 1970s, and have remained consistently lower than 2 mg l^{-1} in most years since. Similar hindcasts by Turner et al. (2006) corroborate the findings in Fig. 4. Results of model hindcasts are consistent with the limited historical oxygen concentration data collected between 1970 and 1985, before the shelfwide surveys began (Turner and Allen 1982; Rabalais et al. 1999, 2002). They are additionally supported by retrospective analyses of sedimentary records, including organic carbon accumulation rates (Eadie et al. 1994), biogenic silica content (Turner and Rabalais 1994), and stratigraphic records of benthic foraminifera (Sen Gupta et al. 1996; Platon and Sen Gupta 2001; Platon et al. 2005). Translating these empirical lines of evidence into shelfwide conditions is difficult because of the relatively few sampling locations and the significant horizontal spatial heterogeneity in the sediment record. However, the significant changes since the middle of the last century from locations where sediment cores have been taken are consistent with changes in riverine nitrate fluxes (Fig. 3).

Model results support the view that large-scale reductions in the nitrogen flux of the Mississippi River would eventually lead to a decrease in areal extent and severity of hypoxia (Fig. 5). Forecasts of the areal extent of hypoxia under various load reduction scenarios conducted by Scavia et al. (2003) suggested that 40-45% reductions in the total nitrogen flux during May and June, relative to the 1980-1996 average, will be required to reduce the extent of hypoxia below 5,000 km^2 (Fig. 5). The three-dimensional model developed by Bierman et al. (1994) did not have the spatial resolution required to forecast changes in the areal extent of hypoxia. Nevertheless, the forecasting of subpycnoclinal oxygen concentrations indicated that decreases in riverine nitrogen flux of 30-50% would result in a 35-50% increase in oxygen concentrations (Fig. 5; LimnoTech, Inc. 1995; Bierman et al. 2001). Similar decreases in phosphorus flux were less effective in increasing subpycnoclinal oxygen levels (LimnoTech, Inc. 1995). This is consistent with experimental observations (Ammerman 1992; Lohrenz et al. 1997, 1999; Rabalais et al. 2002) and model results (Fig. 6; LimnoTech, Inc. 1995) indicating that phytoplankton production over much of the area affected by hypoxia is limited by nitrogen.

TOWARDS AN INTEGRATED HYPOXIA FORECASTING SYSTEM

It is impossible to predict the future, especially in detail, and this applies to both simple and complex models. Yet, it is possible to design scenarios that involve specified values and/or ranges for external forcing functions and to conduct forecast simulations with both simple and complex models. Model results should be expected to be reasonable and useful for management decisions only to the extent that actual future external forcing functions match those in the forecast scenarios.

Simple and complex models each have their own unique sets of advantages and drawbacks. An advantage of simple models is that their data requirements for inputs and calibration/validation are much less extensive than for complex models. One consequence of this advantage is that simple models (e.g., Justić et al. 2002; Scavia et al. 2003) can often be applied/tested using data from much longer periods of record than complex models (e.g., Bierman et al. 1994). The ability to test simple models for long periods of record confers them with a degree of robustness that strengthens their ability to forecast future conditions, subject to the above caveats. The offset for this advantage is that simple models provide information on only a limited number of parameters, e.g., average oxygen concentrations at a single stations (Justić et al. 2002), or summer average hypoxic area (Scavia et al. 2003). Consequently, simple hypoxia models can indeed be valuable as forecasting tools, but they do so at the expense of providing understanding of the complex cause-effect mechanisms governing the development of hypoxia.

An advantage of complex models, if they are well-formulated and tested, is that they can provide understanding of cause-effect mechanisms that are impossible to derive solely from observational data (e.g., mass balance components for carbon, oxygen and nutrients; relative importance of light, temperature and nutrients in limiting primary production; transport and fate of organic carbon). A disadvantage of complex models is their extensive data requirements for inputs, calibration and validation. Consequently, it is much more difficult to apply complex models for long periods of record and confirm their robustness over the full dynamic ranges of their external forcing functions (e.g., Bierman et al. 1994 model calibration periods - three summer snapshots, 1985, 1988 and 1990). Complex models can also be valuable as forecasting tools, but it is much more difficult and expensive to develop, calibrate and validate such models and demonstrate their robustness over the full range of conditions for which they were designed.

The existing Gulf's hypoxia models support the view that large-scale reductions in the nitrogen flux of the Mississippi River would eventually lead to a decrease in areal extent and severity of hypoxia. Yet, because most current forecasting models have inadequate spatial resolution, they are not able to predict how the location and the volume of hypoxic waters will change in response to nutrient reduction. The exception to this is the relatively simple, one horizontal-dimensional bio-physical model of Scavia et al. (2003, 2004) that does predict areal extent and general location of the hypoxic region. Thus, there is an apparent need for model development along two fronts: 1) refinement of relatively simple models that can provide forecast rigor at the expense of detailed mechanistic insight, and 2) enhancement of more complex 3-D models that can help describe and dissect controls and consequences at the expense of forecast rigor.

Potential areas of refinement for the simple biophysical models (e.g., Scavia et al. 2003, 2004) include extending areal forecasts to volume forecast through regression, considerations of higher spatial resolution, modeling of the horizontal distribution of primary production along the river plume that generates distributed sources of organic material to sub-picnocline regions, and moving from steady-state to time-dependent solutions. Regression models (e.g., Goolsby et al. 2003, Turner et al. 2005, 2006) can also be expanded by considering other potential forms of nutrient limitation, different spatial and temporal frameworks, and by included additional years of observations.

The more complex 3-D models can be used to drive research questions as hypothesis testing and identify missing data that need to be collected, so that the effects of uncertain future conditions (e.g., climate change) can be assessed before they happen. These models can be refined by incorporating data acquisition, remote sensing, multi-layered databases, graphical user interface, visualization and internet tools to help refine our understanding of the ecological and physical factors affecting hypoxia (Fig. 7). For example, recent developments in adjoint methods provide numerous opportunities to use numerical models for data assimilation, array design, and sensitivity studies (Moore et al. 2004), and to couple these models with ocean observing systems. Because of the critical roles of local wind and buoyancy forcing in the development of hypoxia, even the most complex models will not be able to forecast the spatial extent of hypoxia beyond a few days to a week into the future. Currently, our ability to predict weather patterns is limited and longer term predictions of hypoxia must be based on statistical wind patterns and flow conditions. Hydrodynamic models can be used to examine the relative importance of various factors controlling stratification, and extend the existing statistical models of hypoxia to include more realistic representations of stratification.

There are a number of hydrodynamic models that simulate circulation in the Gulf of Mexico and the Caribbean Seas. Operational models are run by the Naval Research Laboratory (http://www7320.nrlssc.navy.mil/ATLhycom1-12/gom1.html) and Texas A&M University (http://seawater.tamu.edu/tglo/). These models focus predominantly on Gulf-wide circulation and the Loop Current and Loop Current Eddy system (Oey et al. 2005). Although the Loop Current system affects the circulation over the Texas-Louisiana shelf, deep ocean circulation is typically secondary to local wind and buoyancy forcing on the inner shelf, inside of the 50 meter isobath where hypoxia usually occurs (Rabalais et al. 1999). Upwelling wind stress, for example, can cause fresh water to pool over the Texas-Louisiana shelf (Morey et al. 2005). Buoyant plumes are difficult to simulate because of both strong advection and active mixing throughout the plume. Nevertheless, there have been many recent advances in simulation of buoyancy driven flows that are relevant to the Mississippi/Atchafalaya River plume system (Yankovsky and Chapman 1997; Pullen and Allen 2000; Fong and Geyer 2001; Garvine 2001; Garcia Berdeal et al. 2002; Hetland 2005; Hetland and Signell 2005). For example, Hetland (2005) provided a framework for setting up and analyzing numerical simulations of buoyant plumes, and this approach was used as a basis for shelf-scale hydrodynamic simulations of the Mississippi/Atchafalaya River plume system (Hetland and DiMarco in review).

In addition to developing complex 3-D hypoxia models, it is equally important to refine model algorithms by including the latest findings from observational studies in the region. For example, none of the existing hypoxia models describes a succession from lightly-silicified diatoms to heavily-silicified diatoms, which may be an important controlling mechanism for Gulf hypoxia development (Dortch et al. 2001; Turner et al. 1998; Turner 2001). Another area of concern that needs to be addressed in model algorithm development relates to the benthic oxygen cycling. Benthic photosynthesis has been repeatedly measured on the Louisiana shelf (Dortch et al. 1994; Rowe et al. 1995), yet this oxygen source is not explicitly included in models that have been used to forecast Gulf's hypoxia (e.g., Bierman et al. 1994; Justić et al. 2002; Scavia et al. 2003, 2004). The model developed by Bierman et al. (1994) did include sub-pycnoclinal primary production and model simulations revealed that this oxygen source had significant impact on bottom oxygen concentrations west of the Atchafalaya River.

Estimating the relative forcings of biology and physics as controls of hypoxia in relatively stagnant bottom waters remains one of the biggest challenges in hypoxia modeling. Conventional oxygen budgets based on oxygen concentration measurements are not particularly helpful in this regard because effects of biological factors are masked by physical factors, and vice-versa. A decrease in bottom oxygen content, for example, may be a result of benthic or water-column respiration. Similarly, an increase in the oxygen content may be an effect of in situ photosynthesis, or a consequence of oxygen influx due to advection or diffusion. As a result, conventional hypoxia models often suffer from errors in model parameterization and excessive use of default parameters. In more recent years, a second approach to measuring oxygen dynamics has been developed that uses oxygen isotopes in addition to the more conventional oxygen concentration measurements. Most work with oxygen isotope budgets has focused on open ocean systems (e.g., Bender and Grande 1987; Quay et al. 1993), with important contributions also made in studies of the Amazon River system (Quay et al. 1995). Recently, Quiñones-Rivera et al. (in review) proposed a novel dual-budget approach aimed at quantifying oxygen sources and sinks in the Gulf's hypoxic zone. The approach is based on the partitioning of oxygen dynamics among the key biological and physical processes using oxygen isotopes, in addition to budget studies based on oxygen concentration measurements. Preliminary model simulations suggested that $\delta^{18}O$ values often reveal potential problems in model parameterization in spite of the fact that models correctly predict oxygen concentrations. This type of "mistaken prediction" is very useful in the overall modeling, forcing new model development. For example, Justić et al. (in preparation) have used the measured oxygen concentrations and oxygen isotopes to estimate maximum potential benthic photosynthesis that would explain the anomalously low $\delta^{18}O$ values in hypoxic bottom waters of the northern Gulf of Mexico.

THE NEXT 50 YEARS?

A scientific consensus now exists that the buildup of greenhouse gases in the atmosphere is warming the earth (IPCC 2001). The last decade of the 20th century was the warmest on record, and paleo-records indicate that recent warming has no counterpart in the last 1000 years (Crowley 2000). The global Earth's temperatures increased by almost 1 ^{o}C during the last 150 years (Jones et al. 1999), and general circulation models (GCMs) have projected further temperature increases of 1-6 ^{o}C over the next 100 years (IPCC 2001). An increase in global temperatures of such a magnitude is expected to produce a general intensification of the hydrologic cycle that would be manifested in increased global precipitation, evapotranspiration and runoff (Miller and Russell 1992). Also, hydrologic extremes such as floods and droughts may become more common and more intense (Easterling et al. 2000). A modeling study that examined the impacts of global warming on the annual discharge of the 33 largest rivers of the world (Miller and Russell 1992) suggested that the average annual discharge of the Mississippi River would increase 20% if the concentration of atmospheric CO_2 doubled. Other studies, however, have shown that runoff estimates for the Mississippi River differed greatly between the Canadian model and the Hadley model (Wolock and McCabe 1999). The annual runoff of the

Mississippi River, for example, was projected to decrease 30% for the Canadian model, but increase 40% for the Hadley model by the year 2099. Thus, in spite of the uncertainties in model projections, the impacts of global climate change on Mississippi River freshwater and nutrient fluxes, and ultimately on hypoxia in the northern Gulf of Mexico, may possibly be large.

Climate change, if manifested by increased global temperatures and enhanced hydrologic cycle, may influence the Gulf's coastal region in two major ways (Fig. 8). First, the magnitude and seasonal patterns of freshwater and nutrient inputs would be affected, which could have an immediate effect on nutrient-enhanced coastal productivity. Also, the fundamental characteristics of the physical environment would likely change, thereby affecting the susceptibility of this ecosystem to eutrophication. In this respect, climate variability would interfere with nutrient management efforts in the Mississippi River Basin. It is difficult at this time to reliably predict future trends in the Mississippi River nutrient fluxes. While it is likely that global riverine nitrogen flux will continue to increase in response to increased human population with its concomitant increased use of agricultural fertilizers (Tilman et al. 2001; Howarth et al. 2002), future estimates for the Mississippi River Basin are not available. Also, nitrate concentrations in the Mississippi River may increase in response to an increase in precipitation and freshwater discharge (Goolsby et al. 1999; Justić et al. 2003b), or decrease as a result of nutrient control efforts in the Mississippi River Basin (McIsaac et al. 2001; Task Force 2001). Nitrate accumulates in soils and underground waters during dry years, and is flushed into streams and the main river channel during wet years (Goolsby et al. 1999). Also, a higher discharge decreases the water residence times in canals, lakes and small streams in the upper parts of the watershed. This reduces nitrogen losses due to denitrification (Howarth et al. 1996; Alexander et al. 2000), and leads to higher nitrate concentration in the mainstem of the river.

The data clearly show that dry years followed by subsequent wet years tend to produce the largest increases in nitrate flux (Goolsby et al. 1999; Justić et al. 2003b). Thus, unless anthropogenic nitrogen inputs to watersheds are reduced, higher and more variable precipitation, projected by many climate models (Wolock and McCabe 1999; Easterling et al. 2000), would enhance nitrate delivery to the Gulf. Riverine phosphorus concentrations have generally paralleled the increasing nitrogen concentrations in watersheds with significant anthropogenic influence (Marchetti et al. 1989; Turner and Rabalais 1991; Howarth et al. 1996). Silicate concentrations, however, have remained constant, or decreased in some rivers (Justić et al. 1995a, 1995b).

Because of high degree of sensitivity of hypoxia to climate-driven variations in the Mississippi River freshwater and nutrient fluxes, models should be developed within the framework of a larger hypoxia forecasting system (Fig. 7; Justić et al. in preparation; Donner and Scavia in review). In a series of modeling studies Justić et al. (2003a) examined the potential impacts of future climate variability on nutrient-enhanced productivity and hypoxia in the northern Gulf of Mexico (Table 2). Model scenarios were based on projected changes in the Mississippi River discharge, Mississippi River nitrate flux, and ambient water temperatures. The results were compared to the nominal model simulation, in which the model was forced by the observed time-series of temperature, riverine freshwater discharge, and nitrate flux over a 45-year period (1955-2000). Simulations of the nominal model identified the mid 1970s as a start of the recurring hypoxia in the lower water column, and predicted a total of 19 years with hypoxia between 1955 and 2000. These results are in good agreement with the timing of first reports documenting hypoxia in the northern Gulf of Mexico (Rabalais and Turner, 2001), and are additionally supported by the retrospective analyses of sedimentary records (Turner and Rabalais

1994). For a scenario with 30% decrease in the average Mississippi River discharge (Scenario 1), the model predicted 8 years with hypoxia, which is a 58% decrease in frequency relative to the nominal model dynamics. For a scenario with 20% increase in the average Mississippi River discharge (Scenario 3), the model predicted a 37% increase in frequency of hypoxia. For a scenario with 4^{o}C increase in the average temperatures of the northern Gulf of Mexico (Scenario 4), the model predicted an increase in the frequency of hypoxia of 32%. Finally, for a scenario with 4^{o}C increase in the average temperatures of the northern Gulf of Mexico and a 20% increase in the average Mississippi River discharge (Scenario 5), the model predicted 31 year with hypoxia, which is an increase of 63%. A 30% decrease in the Mississippi River nitrate concentrations (Scenario 6) would result in a 37% decrease in the frequency of hypoxia. Nevertheless, a 20% increase in the Mississippi River discharge would offset a decrease in the frequency of hypoxia resulting from a 30% decrease in the anthropogenic nitrogen flux. Thus, depending on the assumptions about directions and magnitude of future changes in freshwater inflow, both major increases and decreases in the frequency of hypoxia are possible.

Results from the simpler model (Scavia et al. 2003) indicate that a 20% increase in nitrate load over the 1980-1996 mean would increase the size of the hypoxic zone by 26%, from the 1980-1996 simulation mean of 12,900 km^2, to 16,200 km^2. Donner and Scavia (in review) show that year-to-year variability in central U.S. climate must be considered in developing nutrient management policy because precipitation in the previous November-December and precipitation in March-April-May is a strong predictor of spring nitrate flux to the Gulf of Mexico. They forecast that during a wet year, a nitrogen reduction of 50-60% – close to twice the Action Plan recommended target – is required to meet the goal of reducing the hypoxia zone to less than 5,000 km^2 in size. While there is significant uncertainty in these climate scenarios, it is important to note that this potentially warmer-wetter scenario is capable of compensating for management-based nitrogen load reductions.

CONCLUSIONS

Forecasts of the areal extent of Gulf's hypoxia under various load reduction scenarios suggested that 40-45% reductions in the total nitrogen flux during May and June, relative to the 1980-1996 average, will be required to reduce the extent of hypoxia below 5,000 km^2. Similar decreases in phosphorus flux were less effective in increasing subpycnoclinal oxygen levels. Forecasts considering inter-annual and long-term changes in precipitation suggest larger reductions in nutrient loads may be required to compensate for increased water (and thus nutrient) flux to the Gulf.

The existing Gulf's hypoxia models support the view that large-scale reductions in the nitrogen flux of the Mississippi River would eventually lead to a decrease in areal extent and severity of hypoxia. Yet, because most current forecasting models have inadequate spatial resolution, they are not able to predict how the location and the volume of hypoxic waters will change in response to nutrient reduction. Thus, there is an apparent need for model development along two fronts: 1) refinement of relatively simple models that can provide forecast rigor at the expense of detailed mechanistic insight, and 2) enhancement of more complex 3-D models that can help describe and dissect controls and consequences at the expense of forecast rigor. Simple models will be most useful for providing long-range forecasts of responses to policy changes within the Mississippi basin because their relatively simple framework enables statistical treatment of changes in weather and climate patterns. More complex 3-D models are needed to simulate detailed changes in severity/areal extent/volume of hypoxic waters under different potential anthropogenic and climate scenarios. In both cases, it is important to refine model algorithms by including the latest findings from observational studies in the region. A particular area of concern that needs to be addressed in model algorithm development relates to the benthic oxygen cycling. Benthic photosynthesis has been repeatedly measured on the Louisiana shelf, yet this oxygen source is not explicitly included in models that have been used to forecast Gulf's hypoxia.

Because of high degree of sensitivity of hypoxia to climate-driven variations in the Mississippi River freshwater and nutrient fluxes, models should be developed within the framework of a larger hypoxia forecasting system. Such a system of simple and complex models would allow models to be refined by incorporating data acquisition, remote sensing, multi-layered databases, graphical user interface, visualization and internet tools. It would help communities that need long-term and near-real time forecasts, e.g., managers who need models to develop realistic nutrient management scenarios, and, fishermen who want to know where hypoxic zone is located. Forecasts also should increase Gulf's hypoxia "visibility" for the public at large, and so increase public support to resolve this national environmental problem.

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REFERENCES

Ambrose, R. B. Jr., T. A. Wool, J. P. Connoly and R. V. Schanz. 1988. WASP4, A hydrodynamic and water quality model - model theory, users manual, and programmer's guide. U. S. Environmental Protection Agency, Environmental Research Laboratory. Athens, Georgia. EPA/600/3-87/039.

Ambrose, R. B., T. A. Wool and J. L. Martin. 1993. The Water Quality Analysis Simulation Program, WASP5, Part A: Model Documentation, Version 5.10; Part B: The WASP5 Input Dataset, Version 5.10. US Environmental Protection Agency, Environmental Research Laboratory, Athens, GA.

Ammerman, J. V. 2002. Seasonal variation in phosphate turnover in the Mississippi River plume and the inner Gulf Shelf: Rapid summer turnover, p. 69-75. In Nutrient Enhanced Coastal Ocean Productivity. Publication Number TAMU-SG-92-109, Sea Grant Program, Texas A&M University, Galveston, Texas.

Bender, M. L. and K. Grande. 1987. Production, respiration and the isotope geochemistry of O_2 in the upper water column. Global Biogeochemical Cycles 1:49-59.

Bierman, V. J. Jr., S. C. Hinz, W. J. Jr. Wiseman, N. N. Rabalais and R. E. Turner. 2001. Forecasting hypoxia in the Gulf of Mexico: Responses to nutrient loadings from the Mississippi River Basin. Presentation at Coastal Zone 01, Cleveland, Ohio, July 18, 2001.

Bierman, V. J. Jr., S. C. Hinz, D. W. Zhu, W. J. Jr. Wiseman, N. N. Rabalais and R. E. Turner. 1994. A preliminary mass balance model of primary production and dissolved oxygen in the Mississippi River Plume/Inner Gulf. Estuaries 17:886-899.

Cerco, C. F. and T. M. Cole. 1993. 3-dimensional eutrophication model of Chesapeake Bay. Journal of Environmental Engineering119:1006-1025.

Cerco, C. F. and T. M. Cole. 1995. User's guide to the CE-QUAL-ICM three-dimensional eutrophication model. U.S. Army Corps of Engineers, Waterways Experiment Station, technical report EL-95-15.

Chen, C., H. Liu and R. C. Beardsley. 2003. An unstructured grid, finite-volume, three-dimensional, primitive equation ocean model: application to coastal ocean and estuaries. Journal of Atmospheric and Oceanic Technology 20:159-186.

Chen, C., D. A. Wiesenburg and L. Xie. 1997. Influences of river discharge on biological production in the inner shelf: A coupled biological and physical model of the Louisiana-Texas Shelf. Journal of Marine Research 55:293-320.

Crowley, T. J. 2000. Causes of climate change over the past 1000 years. Science 287:270-277.

D'Elia, C. J., J. G. Sanders and W. R. Boynton. 1986. Nutrient enrichment studies in a coastal plain estuary: phytoplankton growth in large-scale, continuous cultures. Canadian Journal of Fisheries and Aquatic Sciences 43:397-406.

Donner, S. D. and D. Scavia. How climate controls the flux of nitrogen by the Mississippi River and the development of hypoxia in the Gulf of Mexico. Limnology and Oceanography (In review).

Dortch, Q., N. N. Rabalais, R. E. Turner and N. A. Qureshi. 2001. Impacts of changing Si/N ratios and phytoplankton species composition, pp. 37-48. In: N. N. Rabalais and R. E.

Turner (eds.), Coastal Hypoxia: Consequences for Living Resources and Ecosystems. Coastal and Estuarine Studies 58, American Geophysical Union, Washington, D.C.

Dortch, Q., N. N. Rabalais, R. E. Turner and G. T. Rowe. 1994. Respiration rates and hypoxia on the Louisiana shelf. Estuaries 17:862-872.

Eadie, B. J., B. A. McKee, M. B. Lansing, J. A. Robbins, S. Metz and J. H. Trefry. 1994. Records of nutrient-enhanced coastal ocean productivity in sediments from the Louisiana continental shelf. Estuaries 17:754-765.

Easterling, D. R., G. A. Meehl, C. Parmesan, A. A. Changnon, T. R. Karl and L. O. Mearns. 2000. Climate extremes: observations, modeling and impacts. Science 289:2068-2074.

Fong, D. A. and W. R. Geyer. 2001. Response of a river plume during an upwelling favorable wind event. Journal of Geophysical Research 106(C1):1067–1084.

Garvine, R. W. 2001. The impact of model configuration in studies of buoyant coastal discharge. Journal of Marine Research 59(2):193–225.

Garcia Berdeal, I., B. M. Hickey and M. Kawase. 2002. Influence of wind stress and ambient flow on a high discharge river plume. Journal of Geophysical Research 107(C9): 3130, doi:10.1029/2001JC000932.

Goolsby, D. A., W. A. Battaglin, G. B. Lawrence, R. S. Artz, B. T. Aulenbach, R. P. Hooper, D. R. Keeney and G. J. Stensland. 1999. Flux and Sources of Nutrients in the Mississippi-Atchafalaya River Basin, Topic 3 Report for the Integrated Assessment of Hypoxia in the Gulf of Mexico. NOAA Coastal Ocean Program Decision Analysis Series No. 17, NOAA Coastal Ocean Program, Silver Springs, Maryland, pp. 130.

Goolsby, D. A., N. N. Rabalais and B. T. Aulenbach. 2003. Using Mississippi River streamflow and nitrate concentrations to estimate the area of the Gulf of Mexico hypoxic zone. 17th

Biennial Conference of the Estuarine Research Federation, Seattle, WA, September 14-18, 2003 (Abstract).

Hetland, R. D. 2005. Water mass structure of wind-forced river plumes. Journal of Physical Oceanography 35:1667-1688.

Hetland, R. D. and S. F. DiMarco. The effects of bottom oxygen demand in controlling the structure of hypoxia on the Texas-Louisiana shelf. Journal of Marine Systems (In review).

Hetland, R. D. and R. P. Signell. 2005. Modeling coastal current transport in the Gulf of Maine. Deep Sea Research II 52:2430-2449.

Howarth, R. W., G. Billen, D. Swaney, A. Townsend, N. Jaworski, K. Lajtha, J. A. Downing, R. Elmgren, N. Caraco, T. Jordan, F. Berendse, J. Freney, V. Kudeyarov, P. Murdoch and Z.-L. Zhu. 1996. Regional nitrogen budgets and riverine N & P fluxes for the drainages to the North Atlantic Ocean: Natural and human influences. Biogeochemistry 35:75-139.

Howarth, R. W., E. W. Boyer, W. J. Pabich and J. N. Galloway. 2002. Nitrogen use in the United States from 1961-2000 and Potential Future Trends. Ambio 31:88-96.

IPCC (Intergovernmental Panel on Climate Change). 2001. Climate Change 2001: The Scientific Basis, Contribution of Working Group I to the Third Assessment Report, Cambridge University Press, Cambridge, pp. 881.

Justić, D., N. N. Rabalais and R. E. Turner. 1995b. Stoichiometric nutrient balance and origin of coastal eutrophication. Marine Pollution Bulletin 30:41-46.

Justić, D., N. N. Rabalais and R. E. Turner. 1996. Effects of climate change on hypoxia in coastal waters: A doubled CO2 scenario for the northern Gulf of Mexico. Limnology and Oceanography 41:992-1003.

Justić, D., N. N. Rabalais and R. E. Turner. 1997. Impacts of climate change on net productivity of coastal waters: Implications for carbon budget and hypoxia. Climate Research 8:225-237.

Justić, D., N. N. Rabalais and R. E. Turner. 2002. Modeling the impacts of decadal changes in riverine nutrient fluxes on coastal eutrophication near the Mississippi River Delta. Ecological Modelling 152:33-46.

Justić, D., N. N. Rabalais and R. E. Turner. 2003a. Simulated responses of the Gulf of Mexico hypoxia to variations in climate and anthropogenic nutrient loading. Journal of Marine Systems 42:115-126.

Justić, D., N. N. Rabalais and R. E. Turner. 2005. Coupling between climate variability and marine coastal eutrophication: Historical evidence and future outlook. Journal of Sea Research 54: 25-35.

Justić, D., N. N. Rabalais, R. E. Turner and Q. Dortch. 1995a. Changes in nutrient structure of river-dominated coastal waters: stoichiometric nutrient balance and its consequences. Estuarine, Coastal and Shelf Science 40:339-356

Justić, D., R. E. Turner and N. N. Rabalais. 2003b. Climatic influences on riverine nitrate flux: implications for coastal marine eutrophication and hypoxia. Estuaries 26:1-11.

Limno-Tech, Inc. 1995. Estimated Responses of Water Quality on the Louisiana Inner Shelf to Nutrient Load Reductions in the Mississippi and Atchafalaya Rivers. Stennis Space Center, Mississippi: U.S. Environmental Protection Agency, Gulf of Mexico Program.

Lohrenz, S. E., M. J. Dagg and T. E. Whitledge. 1990. Enhanced primary production in the plume/oceanic interface of the Mississippi River. Continental Shelf Research 10:639-664.

Lohrenz, S. E., G. L. Fahnenstiel, D. G. Redalje, G. A. Lang, X. Chen, X. and M. J. Dagg. 1997. Variations in primary production of northern Gulf of Mexico continental shelf waters linked to nutrient inputs from the Mississippi River. Marine Ecology Progress Series 155:45-54.

Lohrenz, S. E., G. L. Fahnenstiel, D. G. Redalje, G. A. Lang, M. J. Dagg, T. E. Whitledge and Q. Dortch. 1999. The interplay of nutrients, irradiance and mixing as factors regulating primary production in coastal waters impacted by the Mississippi River plume. Continental Shelf Research 19:1113-1141.

Marchetti, R., G. Pachetti, A. Provini and G. Crosa. 1989. Nutrient load carried by the Po River into the Adriatic Sea, 1968 - 1987. Marine Pollution Bulletin 20:168-172.

McIsaac G.F., M. B. David, G. Z. Gertner and D. A. Goolsby. 2001. Eutrophication - Nitrate flux in the Mississippi river. Nature 414:166-167.

Miller, J.R. and G.L. Russell. 1992. The impact of global warming on river discharge. Journal of Geophysical Research 97:2757-2764.

Mitsch, W. J., J. W. Day, J. W. Gilliam, P. M. Groffman, D. L. Hey, G. W. Randall and N. Wang. 2001. Reducing nitrogen loading to the Gulf of Mexico from the Mississippi River Basin: Strategies to counter a persistent ecological problem. BioScience 51:373-388.

Moore, A. M, H. G. Arnago, E. Di Lorenzo, B. D. Cornuelle, A. J. Miller and D. J. Neilson. 2004. A comprehensive ocean prediction and analysis system based on the tangent linear and adjoint of a regional ocean model. Ocean Modelling 7:227-258.

Morey, S. L., J. Zavala-Hidalgo and J. J. O'Brien. 2005. The Seasonal Variability of Continental Shelf Circulation in the Northern and Western Gulf of Mexico From a High-Resolution

Numerical Model, p. 203-218. In W. Sturges and A. Fernandez (eds.), Circulation in the Gulf of Mexico: Observations and Models. American Geophysical Union.

Oey, L.-Y., T. Ezer and H.-C. Lee. 2005. Loop Current Rings and Related Circulation in the Gulf of Mexico: A Review of Numerical Models and Future Challenges, p. 31-56. In W. Sturges and A. Fernandez (eds.), Circulation in the Gulf of Mexico: Observations and Models, American Geophysical Union.

Platon, E. and B. K. Sen Gupta. 2001. Benthic foraminiferal communities in oxygen-depleted environments of the Louisiana continental shelf, p. 147-164. In N. N. Rabalais and R. E. Turner (eds.), Coastal Hypoxia: Consequences for Living Resources and Ecosystems. Coastal and Estuarine Studies 58, American Geophysical Union, Washington, D. C.

Platon, E., B. K. Sen Gupta, N. N. Rabalais and R. E. Turner. 2005. Effect of seasonal hypoxia on the benthic foraminiferal community of the Louisiana inner continental shelf: The 20th century record. Marine Micropaleontology 54:263-283.

Pullen, J. D. and J. S. Allen. 2000. Modeling Studies of the Coastal Circulation off Northern California: Shelf Response to a Major Eel River Flood Event. Continental Shelf Research 20:2213–2238.

Quay, P. D., S. Emerson, D. O. Wilbur and C. Stump. 1993. The $\delta^{18}O$ of dissolved O_2 in the surface waters of the Subarctic pacific: A tracer of biological productivity. Journal of Geophysical Research 98:8447-8458.

Quay, P. D., D. O. Wilbur, J. E. Richey, A. H. Devol, R. Benner and B. R. Forsberg. 1995. The ^{18}O:^{16}O of dissolved oxygen in rivers and lakes in the Amazon basin: Determining the ratio of respiration to photosynthesis rates in freshwaters. Limnology and Oceanography 40:718-729.

Quiñones-Rivera, Z. J., B. Wissel, D. Justić and B. Fry. Partitioning oxygen sources and sinks in a stratified, eutrophic coastal ecosystem using stable oxygen isotopes. Marine Ecology Progress Series (In review).

Rabalais, N. N. 2004. Eutrophication, Chapter 21, p. 819-865. In A. R. Robinson, J. McCarthy and B. J. Rothschild (eds.), The Global Coastal Ocean: Multiscale Interdisciplinary Processes, The Sea, Vol. 13, Harvard University Press.

Rabalais, N.N. and R. E. Turner. 2001. Hypoxia in the northern Gulf of Mexico: description, causes and change, p. 1-36. In N. N. Rabalais and R. E. Turner (eds.), Coastal Hypoxia: Consequences for Living Resources and Ecosystems. Coastal and Estuarine Studies 58, American Geophysical Union, Washington, D. C.

Rabalais, N. N., R. E. Turner, D. Justić, Q. Dortch and W. J. Jr. Wiseman. 1999. Characterization of Hypoxia: Topic 1 Report for the Integrated Assessment of Hypoxia in the Gulf of Mexico. NOAA Coastal Ocean Program Decision Analysis Series No. 15, NOAA Coastal Ocean Program, Silver Springs, Maryland, pp. 167.

Rabalais, N. N., R. E. Turner, D. Justić, Q. Dortch, W. J. Jr. Wiseman and B. K. Sen Gupta. 1996. Nutrient changes in the Mississippi River and system responses on the adjacent continental shelf. Estuaries 19:386 - 407.

Rabalais, N. N., R. E. Turner and D. Scavia. 2002. Beyond science into policy: Gulf of Mexico hypoxia and the Mississippi River. BioScience 52:129-142.

Rabalais, N. N., R. E. Turner, W. J. Jr. Wiseman and Q. Dortch. 1998. Consequences of the 1993 Mississippi River flood in the Gulf of Mexico. Regulated Rivers: Research and Management 14:161 - 177.

Rowe, G. T., M. L. Kruz Kaegi, J. W. Morse, G. S. Boland and E. G. Escobar Briones. 2002. Sediment community metabolism associated with continental shelf hypoxia, northern Gulf of Mexico. Estuaries 25:1097-1106.

Scavia, D., D. Justić and V. J. Jr. Bierman. 2004. Reducing hypoxia in the Gulf of Mexico: advice from three models. Estuaries 27:419-425.

Scavia, D., N. N. Rabalais, R. E. Turner, D. Justić and W. J. Jr. Wiseman. 2003. Predicting the response of Gulf of Mexico hypoxia to variations in Mississippi River nitrogen load. Limnology and Oceanography 48:951-956.

Shchepetkin, A. F. and J. C. McWilliams. 2005. The regional oceanic modeling system (ROMS): a split-explicit, free-surface, topographically-following-coordinate oceanic model. Ocean Modelling 9:347-404.

Sen Gupta, B. K., R. E. Turner and N. N. Rabalais. 1996. Seasonal oxygen depletion in continental-shelf waters of Louisiana: Historical record of benthic foraminifers. Geology 24:227-230.

Task Force (Mississippi River Nutrient/Gulf of Mexico Hypoxia Task Force). 2001. Action Plan for Reducing, Mitigating, and Controlling Hypoxia in the Northern Gulf of Mexico. Washington, D.C.: Office of Wetlands, Oceans, and Watersheds, U.S. Environmental Protection Agency.

Tilman, D., J. Fargione, B. Wolff, C. D'Antonio, A. Dobson, R. Howarth, D. Schindler, W. H. Schlesinger, D. Simberloff and D. Swackhamer. 2001. Forecasting agriculturally driven global environmental change. Science 292:281-284.

Trenberth, K. E. and C. J. Guillemot. 1996. Physical processes involved in the 1988 drought and the 1993 flood in North America. Journal of Climate 9:1288-1298.

Turner, R. E. 2001. Some effects of eutrophication on pelagic and demersal marine food webs, p. 371-398. In N. N. Rabalais and R. E. Turner (eds.), Coastal Hypoxia: Consequences for Living Resources and Ecosystems. Coastal and Estuarine Studies 58, American Geophysical Union, Washington, D. C.

Turner, R. E. and R. L. Allen. 1982. Bottom water oxygen concentration in the Mississippi River Delta Bight. Contributions in Marine Science 25:161-172.

Turner, R. E., N. Qureshi, N. N. Rabalais, Q. Dortch, D. Justić, R. F. Shaw and J. Cope. 1998. Fluctuating silicate:nitrate ratios and coastal plankton food webs. Proceedings of the National Academy of Sciences 95:13048-13051.

Turner, R. E. and N. N. Rabalais. 1991. Changes in the Mississippi River water quality this century - Implications for coastal food webs. BioScience 41:140-147.

Turner, R. E. and N. N. Rabalais. 1994. Evidence for coastal eutrophication near the Mississippi river delta. Nature 368:619-621.

Turner, R. E. and N. N. Rabalais. 2003. Linking landscape and water quality in the Mississippi River Basin for 200 years. BioScience 53:563-572.

Turner, R. E., N. N. Rabalais and D. Justić. 2006. Predicting summer hypoxia in the northern Gulf of Mexico: Riverine N, P and Si loading. Marine Pollution Bulletin 52:139-148.

Turner, R. E., N. N. Rabalais, E. M. Swenson, M. Kasprzak and T. Romaire. 2005. Summer hypoxia, northern Gulf of Mexico: 1978 to 1995. Marine Environmental Research 59:65-77.

Wiseman, W. J. Jr., N. N. Rabalais, R. E. Turner, S. P. Dinnel and A. MacNaughton. 1997. Seasonal and interannual variability within the Louisiana coastal current: stratification and hypoxia. Journal of Marine Systems 12:237-248.

Wiseman, W. J. Jr., N. N. Rabalais, R. E. Turner and D. Justić. 2004. Hypoxia and the physics of the Louisiana coastal current. In: Dying and Dead Seas. Climatic versus anthropogenic Causes, NATO Advanced Research Workshop, Liège, Belgium, NATO ASI Series, Kluwer.

Wolock, D. M. and G. J. McCabe. 1999. Estimates of runoff using water-balance and atmospheric general circulation models. Journal of the American Water Resources Association 35:1341-1350.

Yankovsky, A. E. and D. C. Chapman. 1997. A Simple Theory for the Fate of Buoyant Coastal Discharges. Journal of Physical Oceanography 27:1386–1401.

Table 1. Gulf of Mexico hypoxia models.

Model reference	**Model class**
Bierman et al. (1994)	Simulation
Chen et al. (1997)	Simulation
Wiseman et al. (1997)	Statistical
Justić et al. (1996, 1997, 2002)	Simulation
Rowe (2001)	Simulation
Scavia et al. (2003, 2004)	Simulation
Stow et al. (2005)	Statistical
Turner et al. (2005, 2006)	Statistical
Hetland et al. (in preparation)	Simulation

Table 2. Simulated changes in the average oxygen concentration of the lower water column (10-20 m) in the core of the Gulf's hypoxic zone for a number of climatic and nitrogen loading scenarios (adapted from Justić et al., 2003a). The nominal model was forced using time series of observed monthly values of the Mississippi River discharge (Q) and nitrate concentration (N-NO_3) over a 45-year period, from 1955-2000 (Fig. 3). The investigated model scenarios are based on the available projections of general circulation models (GCMs) for the continental U.S., the Mississippi River, and the northern Gulf of Mexico, as well as the proposed nutrient management goals.

Model scenario	**# of years with hypoxia (< 2 mg O_2 l^{-1})**	**% change relative to the nominal model**
Nominal model	19	-
Scenario 1 (-30% Q)	8	-58
Scenario 2 (1955-1967 N-NO_3)	0	-100
Scenario 3 (+20% Q)	26	+37
Scenario 4 (+4 ^oC)	25	+32
Scenario 5 (+20% Q, +4 ^oC)	31	+63
Scenario 6 (-30% N-NO_3)	12	-37

FIGURE CAPTIONS:

Figure 1. Distribution of frequency of occurrence of mid-summer bottom-water hypoxia over the 60 to 80-station grid (black dots) from 1985 to 2002 (source: N. Rabalais, LUMCON; adapted from Rabalais and Turner 2001).

Figure 2. Areal extent of Gulf hypoxia 1985-2005 (source: N. Rabalais, LUMCON; adapted from Rabalais and Turner 2001). Dashed lines indicate the 1985-2005 average and the Action Plan goal.

Figure 3. Monthly averages (August 1954-May 2000) of the lower Mississippi River discharge (Q), nitrate concentration ($N\text{-}NO_3$), and nitrate flux ($N\text{-}NO_3$ flux). Smoothed curves are estimated third order polynomial fits on 12-month weighted averages (adapted from Justić et al. 2003b, reprinted with permission of Estuarine Research Federation).

Figure 4. Upper panel: Probabilistic hindcast of the areal extent of hypoxia during 1968-2002 (from Scavia et al. 2003, reprinted with permission of American Society of Limnology and Oceanography). Solid curve and error bars represent the 1st, 2nd, and 3rd quartiles from 1000 Monte Carlo simulations. Boxes represent observed hypoxic zone area. Lower panel: Simulated changes in the average bottom (10-20 m) oxygen concentration at a station within the core of the Gulf's hypoxic zone during 1955-2000 (from Justić et al. 2002, reprinted with permission of Elsevier). Shaded area denotes hypoxia.

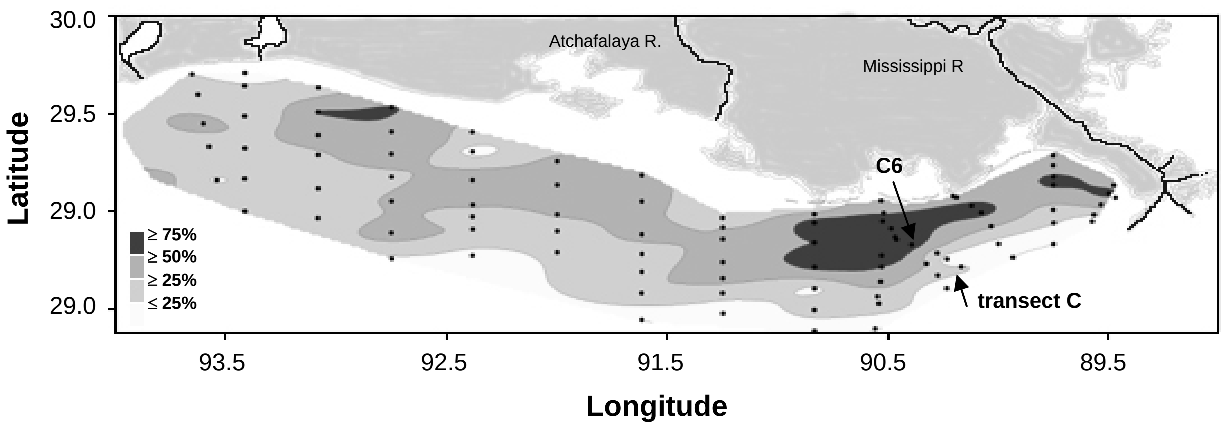
Figure 5. Upper panel: Ensemble forecasts of the responses of hypoxia to changes in riverine nitrogen load (from Scavia et al. 2003, reprinted with permission of American Society of Limnology and Oceanography). Percent reduction is based on the 1980-1996 mean May-June total nitrogen loads. The shaded area contains values between the first and third quartiles from 1,000 simulations. The horizontal bar at 5,000 km^2 represents the Action Plan goal. Lower panel: Simulated increases in subpycnoclinal oxygen concentrations in response to riverine nitrogen load reduction (forecasts from LimnoTech, Inc. 1995). Vertical bars denote the range of model results for different spatial segments.

Figure 6. Simulated changes in the nitrogen and phosphorus limitations along shelf contour between the Mississippi River Delta and the Texas Coast during July 1990 (from LimnoTech, Inc. 1995).

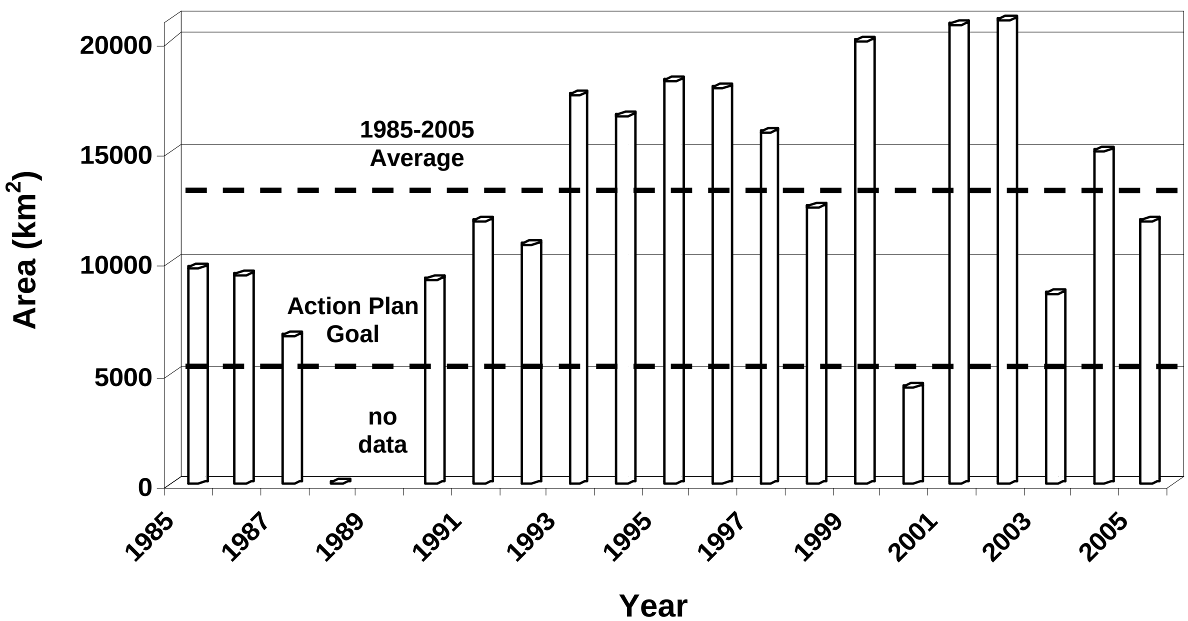
Figure 7. Elements of the Gulf of Mexico Hypoxia Forecasting System. ROMS = Regional Ocean Modeling System (Shchepetkin and McWilliams 2005), FVCOM = Finite Volume Coastal Ocean Model (Chen et al. 2003), WASP = Water Analysis Simulation Program (Ambrose et al. 1988, 1993), CE-QUAL-ICM (Cerco and Cole 1993, 1995), MM5 = Pennsylvania State University / National Center for Atmospheric Research mesoscale model, GUI = Graphical User Interface.

Figure 8. Coupling between climate variability, coastal eutrophication and hypoxia (from Justić et al. 2005, reprinted with permission from Elsevier).

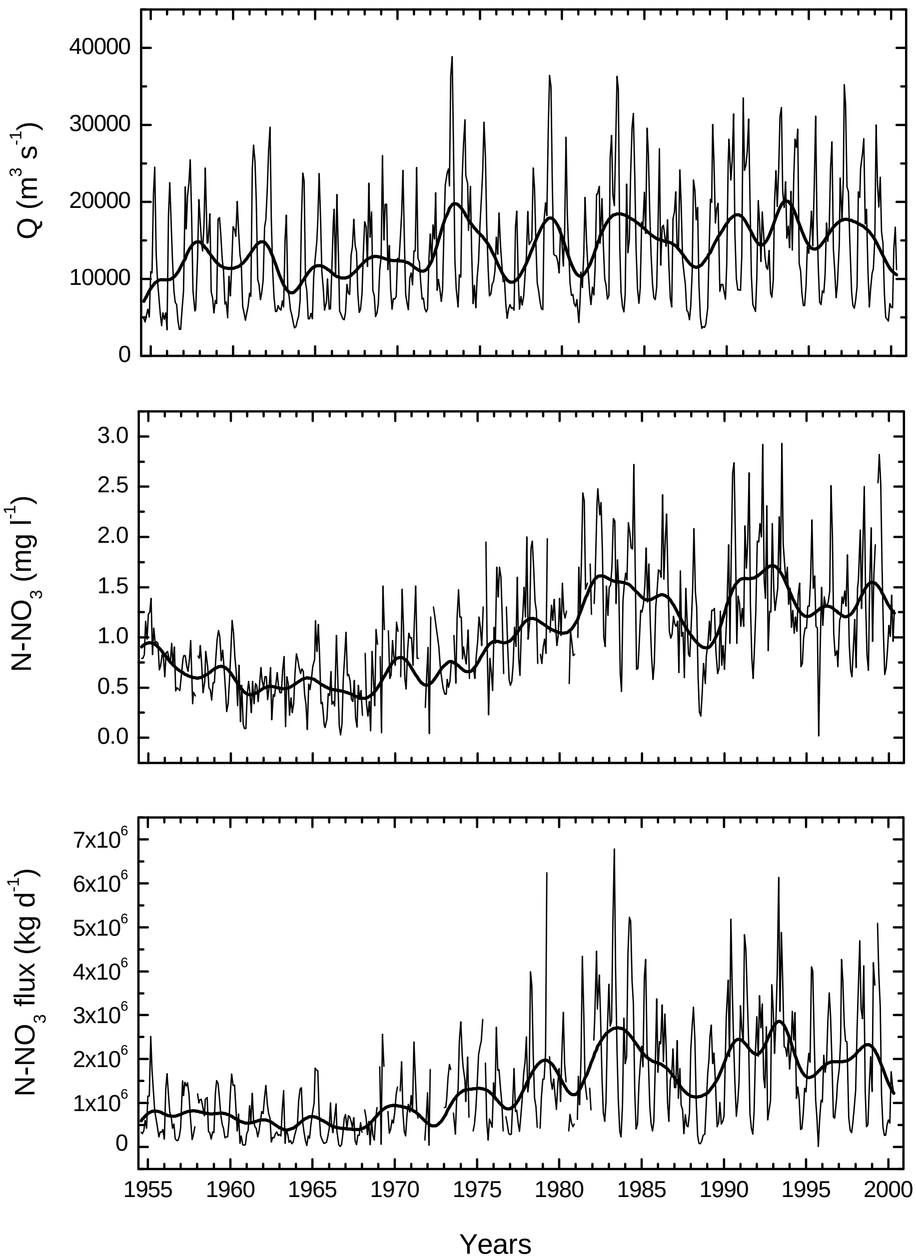
Justić et al., Fig. 1.



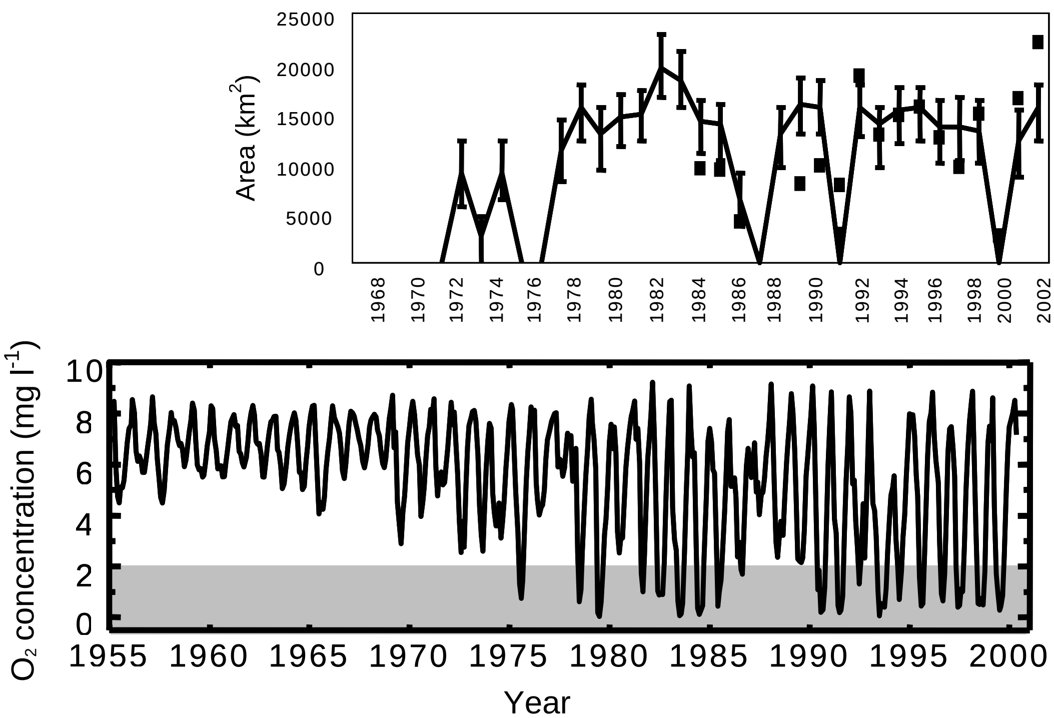
Justić et al., Figure 2.



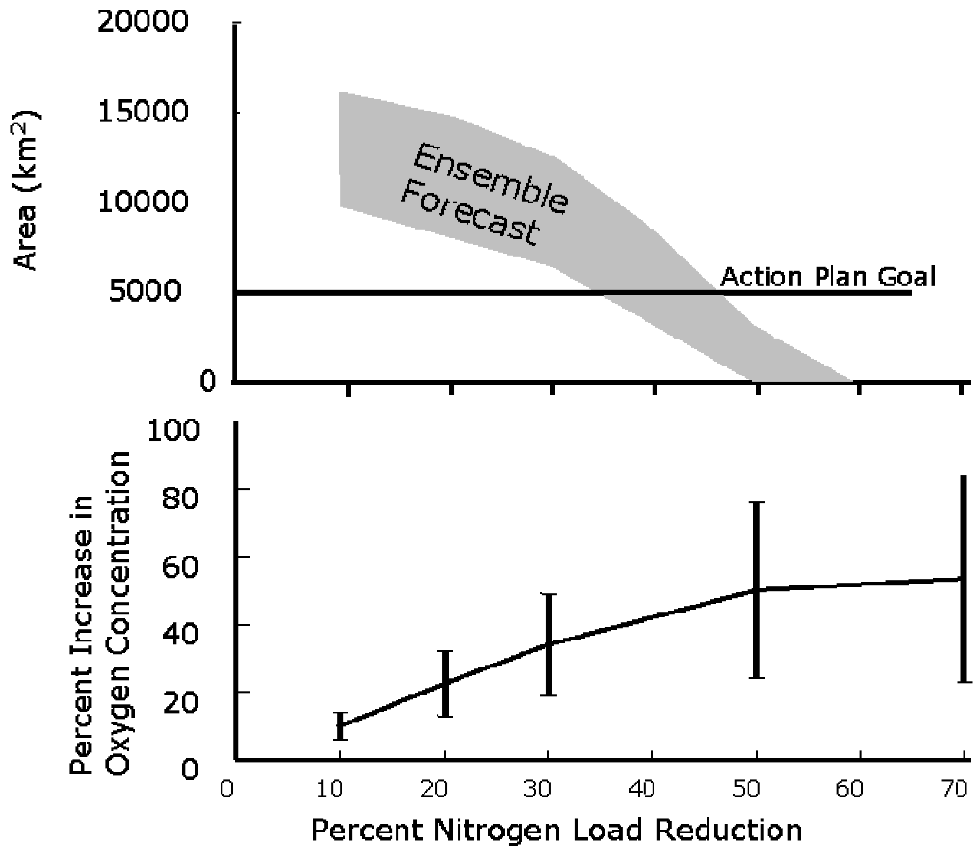
Justić et al., Figure 3.



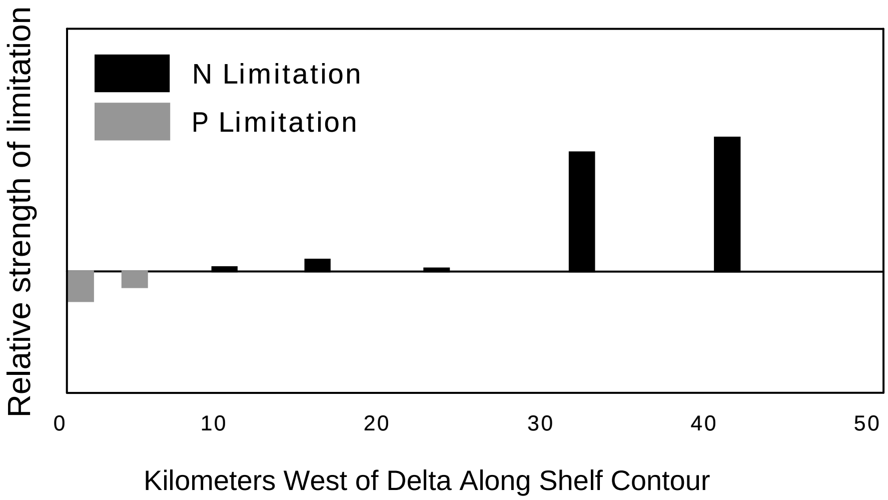
Justić et al., Figure 4.



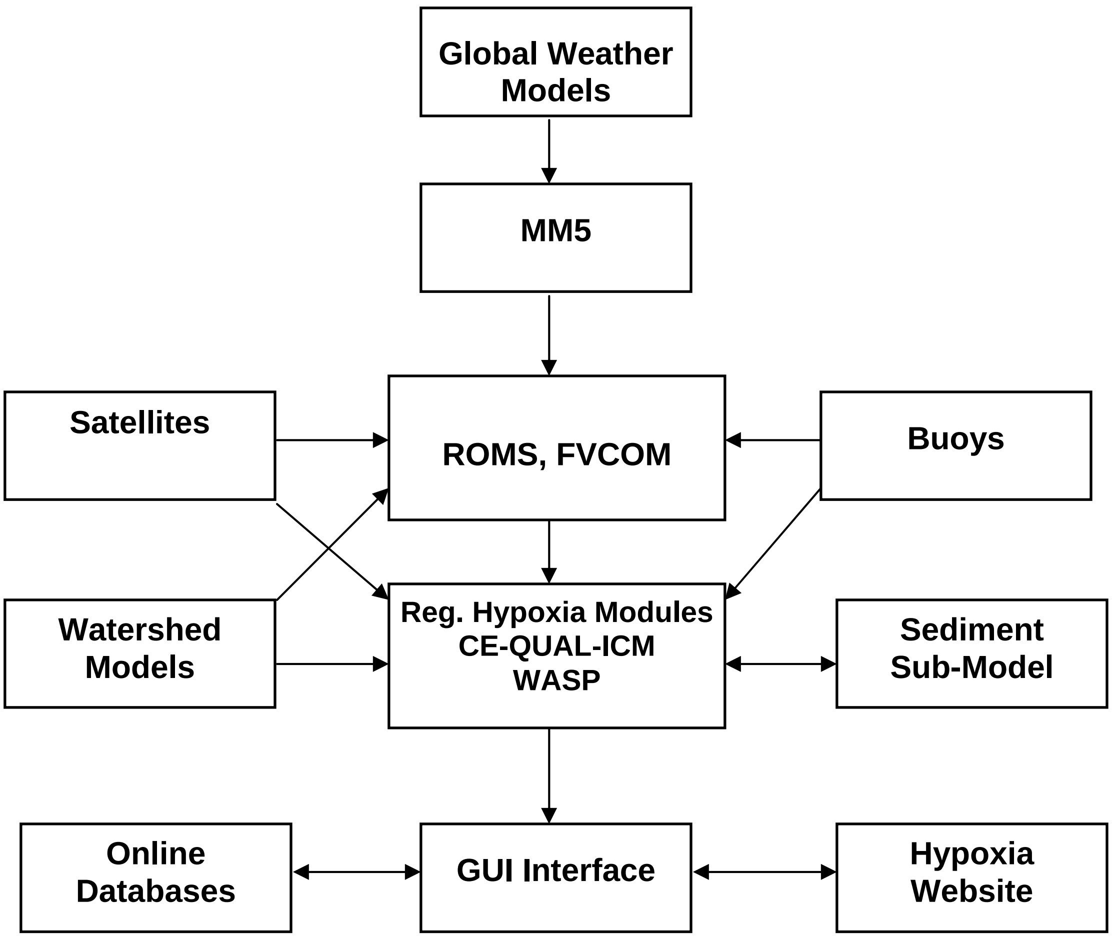
Justić et al., Figure 5.



Justić et al., Figure 6.



Justić et al., Figure 7.



Justić et al., Figure 8.